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UNSOLVED PROBLEMS IN PREDICTING THE BEHAVIOR OF CONCRETE

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U. S. Army Engineer Waterways Experiment Station
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FOREWORD

The manuscript of this paper was prepared at the request of Mr. W. J. Trapp, Air Force Materials Laboratory, Wright-Patterson Air Force Base; Chairman, Planning Committee, Symposium on Correlation of Materials Characteristics with Systems Performance, The Technical Cooperation Program, Panel P-4, Methods of Test and Evaluation, scheduled to be held at Orlando, Florida, on 10-12 May 1967. The manuscript was reviewed and approved for presentation and publication by the Office, Chief of Engineers on 10 April 1967.

Colonel John R. Oswalt, Jr., CE, was Director of the Waterways Experiment Station during the preparation of this paper. Mr. J. B. Tiffany was Technical Director.

UNSOLVED PROBLEMS IN PREDICTING THE BEHAVIOR OF CONCRETE*

by Bryant Mather**

Abstract

The concrete at any given location in a structural element of a structural system in service will manifest its characteristic behavior as a result of the interaction of the properties it possesses with the properties of the specific environment at that location. The properties of the concrete result from the interaction of the requirements established by the specifications for the work and the enforcement thereof during construction. The specifications set forth directly or indirectly requirements for properties of the ingredients of the concrete, for the proportions in which these are to be combined, and for the practices that are to be followed in converting these ingredients into a portion of the finished structural system.

When one is able to relate, on the one hand, the manner and degree to which changes in the properties of the constituent materials, changes in the proportions in which these are used, and changes in the construction practices affect the properties of the finished concrete and, on the other hand, the manner and degree to which the properties of the finished concrete change over time as a function of any particular environmental regime in which the structure may be located, then one will be able to predict not only the properties of a given volume of concrete at a given

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place and at a given time in the future, but also to predict the path by which these properties achieve that state. This would be predicting the behavior of concrete.

The unsolved problems are that we do not now understand how to measure relevant parameters of the environment nor, indeed, to measure and evaluate with any degree of accuracy meaningful properties of the concrete, much less how to predict quantitatively the results of their interaction.

Introduction

The discussions at this symposium have as their purpose the advancement of the art of correlating characteristics of materials with the performance of systems. The particular discussions at this session involve the effects of environment as these interact with material characteristics to affect performance. My title, "Unsolved Problems in Predicting the Behavior of Concrete," is one under which might be described any or all of the work that has been done and the knowledge that has been gained in the past 2000 years concerning the selection of concreting materials and mixtures that are intended to possess the characteristics needed to insure that the resulting concrete structures and structural elements will have the properties they need to insure that the systems in which they are incorporated will interact with the environments in which they are placed so as to insure that the systems will provide the service for which they were constructed to the satisfaction of those they were intended to serve. It would also be appropriate to describe all the projects and programs that

all the workers on concrete research now have in progress or hope in the future to undertake in all the concrete research laboratories in the world. On the other hand, it seems pertinent to note that the failure of a system composed of concrete structural elements to give the desired service frequently results from its failure to have been built according to the principles that were intended to have been followed. Frontinus, in 97 A.D., after listing the material characteristics of concrete needed to provide proper performance of the aqueduct system of Rome, laid the blame on the workmen when he wrote, "All these the workmen know, but few observe." In the following sections of this paper I plan briefly to review what concrete is, to indicate how, because of its nature, it may manifest an infinite range in its properties; to suggest some aspects of the infinite range of environmental effects that may influence its performance; to examine some features of the state of knowledge of the consequences of the interaction of concrete properties with environmental conditions; and finally to propose that asking the proper questions regarding the extension of this knowledge is a delineation of the unsolved problems in predicting the behavior of concrete.

Concrete

Concrete is a construction material that is made by mixing to a degree of homogeneity ingredients having an infinite variety of properties of widely varying significance, proportioned in accordance with a recipe selected according to poorly defined rules. The ingredients are not uniform, either from place to place or batch to batch, or within a batch.

Batches of the mixture are transported by one or more of a variety of methods, discharged into prepared forms of any desired size or shape, which may or may not have previously been provided with reinforcing steel or other items intended to be surrounded by the concrete, and compacted so as to more or less completely fill the form. Once the form is filled, the surface is normally struck off and finished. The mass then undergoes spontaneous chemical and physical changes described as setting, hardening, development of strength, and volume change. During the early stages of spontaneous activity of the mass, when these changes are taking place at the most rapid rates, there is normally some intentional external control of the immediate environment, referred to as "curing," intended to avoid what are regarded as "excessive" changes of temperature or moisture content. Once the mass has gone through its adolescence, which may be a period of from one to 21 days--depending on the circumstances--it is then pretty much on its own.

Concrete is a composite material consisting of two fundamental elements: aggregate and binder or matrix, a discontinuous phase that can be considered as inclusions in a continuous phase. The concrete with which I am familiar is that in which the binder includes a hydraulic cement, which is generally portland cement. Another well-known type of concrete is that in which the binder is a bituminous material. Such bituminous concretes have their major use in the construction of flexible pavements. For convenience, aggregates are considered in two size categories, designated respectively fine aggregate and coarse aggregate, the separation being made at the No. 4 (4760-micron) sieve. Fine aggregate is often spoken of as "sand," and

natural sands are a principal kind of fine aggregate, but many other materials are also used, especially crushed stone, crushed slag, mine tailings, and various crushed sintered materials. The principal materials used as coarse aggregate are gravel, crushed stone, crushed slag, crushed gravel, and expanded clay, shale, slate, or slag. For most applications, the materials used as aggregates are required to be provided in specified ranges of particle-size distribution. It is advantageous to use as much aggregate as possible in each unit volume of concrete so as to reduce the volume of cement required, which reduces cost and reduces the tendency to volume change.

Hydraulic cements are materials that react with water to yield products having cohesiveness and continuity. The extent to which any given cement develops such properties in a given period of time depends on the ratio of the volume of cement to the volume of water with which it is mixed, the chemical activity of the cement, and the degree to which the environment accelerates or retards the progress of the reactions. In the case of portland cement, for example, when the ratio of water to cement exceeds about 20 U. S. gallons per 100 pounds of cement, or when the temperature of the mixture is held below about 11 F, or when the mixture contains more than traces of any of several sugars--such as sucrose--in solution in the mixing water, no significant development of cohesion or continuity will take place.

Properties of Concrete

Concrete has been and may at will be produced to possess, in its final stable mature state, any of an infinite range of properties. It may weigh

anywhere from as little as 10 lb/cu ft to over 300 lb/cu ft. The exceedingly lightweight concretes are produced using air or some other gas as the major aggregate; the exceedingly heavyweight concretes are produced using pieces of metal as aggregate. Both of these extreme classes have their major uses in connection with nuclear applications; the former for blast shock mitigation; the latter for radiation shielding. Concrete may be produced that will set, harden, and develop ultimate unconfined compressive strengths ranging from a very few pounds per square inch to as much as 20,000 psi. The very low-strength concretes are usually produced from mixtures of high gas content and high water to cement ratios; the very high strength concretes require low water to cement ratios and aggregates that themselves have high strength. The rate of hardening may be varied within wide limits. A mixture may be produced that sets and hardens in a few seconds or minutes, usually as a result of the use of a chemical accelerator; or, by the use of appropriate amounts of a chemical retarder, the mixture may remain semifluid and remoldable for many hours or days; lesser degrees of acceleration and retardation are produced by changes in composition of the cement or by changes in the ambient temperature or both.

The foregoing comments concern properties that can be varied at will--controllable performance. More significant to most engineering uses of concrete are variations in properties that affect performance but that occur without having been intended or predicted.

One may encounter an apparently continuous volume of concrete in service of which a portion exhibits observably different behavior from an adjacent portion, thus indicating a nonuniformity either of properties

of the concrete or of the environment. If it can be shown, or assumed with confidence, that the environment has been uniform, one seeks the explanation of the difference in behavior from a difference in properties of the concrete. However, before a meaningful assessment of significance of differences in concrete properties can be made, it is first necessary to develop a hypothesis concerning the kind of environmental interaction that produced the observed effects.

Environmental Effects

The environments in which concrete serves possess a wide variety of properties that interact with the properties of the concrete and result in behavior. Further, the properties of the environment interact with each other. For example, two major environmental influences are temperature and moisture, which together induce temperature change and moisture-content change in concrete. Temperature change in the environment, per se, within ranges where none of the constituents of the concrete undergo changes of phase or state, interacts with concrete to produce temperature change of the concrete that is manifested in behavior as volume change proportional to the coefficient of thermal expansion of the concrete. The behavioral consequences of such volume change can be quite significant, depending on the requirements for volume stability of the structure or structural element, its restraint, its dimensions, the degree to which it has been provided with expansion and contraction joints, the degree to which cracking is significant to satisfactory rendering of the service expected of it, and so forth. However, the consequences of temperature change, per se, on behavior generally are less significant than those of temperature changes

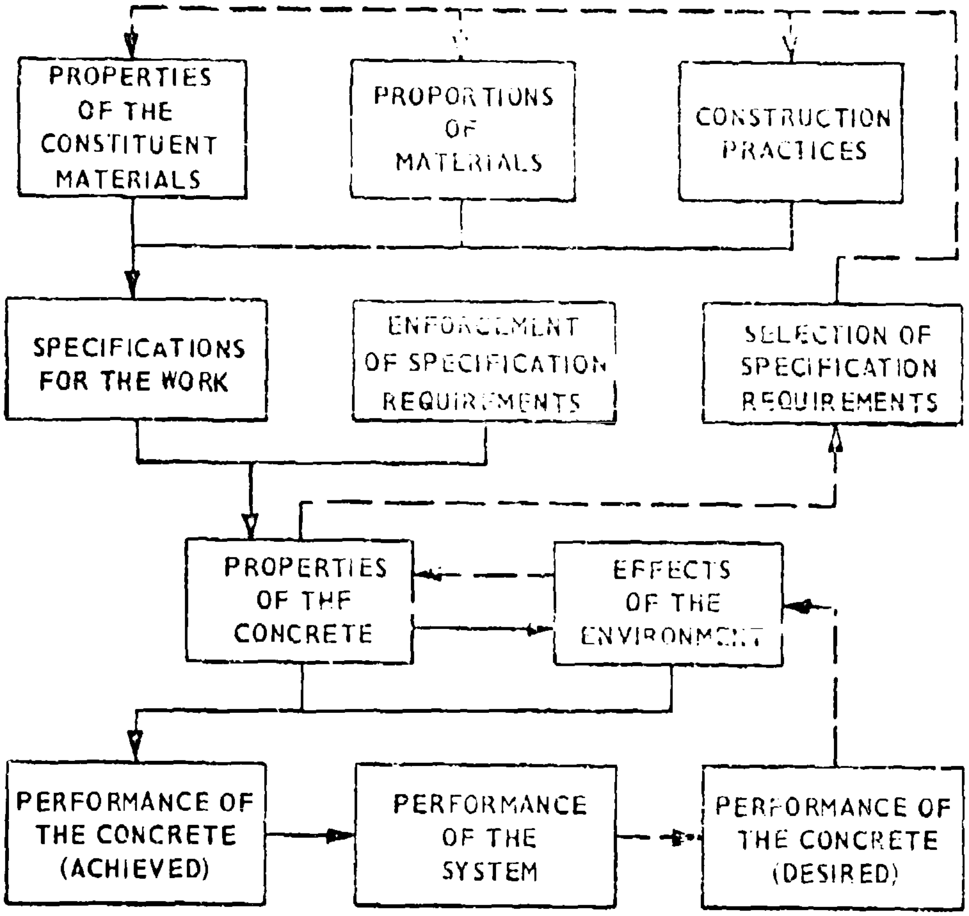
accompanied by moisture-content changes, since a reduction of environmental temperature to levels below the freezing point of water following a development of high-moisture content may cause destruction of the concrete as the water in its large permeable pore spaces undergoes the volume change accompanying the change of state to ice.

Other major properties of the environment include loading, abrasion and chemical attack.

Interactions Affecting Behavior

From the foregoing comments on the nature of concrete, the characteristics that it may possess, and the environmental effects that may influence its behavior, I believe that it is clear that the performance or behavior of a system in which concrete is used--or the performance or behavior of the concrete in that system--can be shown to be controlled in a manner illustrated by fig. 1.

The kind of performance desired depends on the criteria of acceptability for the system. Surface defects, cracks, deflections, removal of surface layers, corners, or edges can be tolerated to much greater degrees in the service of some systems than others. No concrete is inert and unchanging. In the real world all substances alter with time and exposure. Thus the first step is to select criteria of acceptability of performance of the system, and hence for the concrete. A great deal of confusion and even bitterness that is encountered in many different confrontations, ranging from those of the home owner and the home builder to those of the Secretaries of Commerce and Transportation and the House Committee on Public



PROPERTIES OF THE CONSTITUENT MATERIALS
PROPORTIONS OF MATERIALS
CONSTRUCTION PRACTICES
SPECIFICATIONS FOR THE WORK
ENFORCEMENT OF SPECIFICATION REQUIREMENTS
SELECTION OF SPECIFICATION REQUIREMENTS
PROPERTIES OF THE CONCRETE
EFFECTS OF THE ENVIRONMENT
PERFORMANCE OF THE CONCRETE (ACHIEVED)
PERFORMANCE OF THE SYSTEM
PERFORMANCE OF THE CONCRETE (DESIRED)

FIG. 1

Works could be avoided, or at least reduced, if these criteria were adequately defined and agreed upon before any system was created. Assuming that criteria of adequacy have been selected, it is then necessary, as fig. 1 indicates, to consider the environmental effects under which these criteria must be achieved, to select the properties of the concrete that will, when it interacts with these environmental effects, give the desired performance, and thus to select the specification requirements for the work. The diagram suggests that specification requirements fall into three categories: properties of constituent materials, proportions thereof, and construction practices. In many cases it is preferable to specify concrete properties rather than materials, proportions, and practices, but it should be recognized that, when this is done, it merely transfers the responsibility to others to set appropriate requirements on these elements.

Let us consider a hypothetical example. For the past 30 years we have maintained an exposure station for concrete at the mean-tide level on the Atlantic Coast near Eastport, Maine. Specimens there are immersed in sea water twice a day as the tide rises above mean and are exposed to the air when the tide falls below mean. From periodic observation of changes and nondestructive tests for resonant frequency and compressional wave velocity, the changes in concrete properties are monitored as they are affected by this environment. Now suppose it were determined that a navigation lock were to be built on the St. Croix River near Calais, Maine, and the design called for a lift of about 50 ft, a lock chamber about 100 ft deep, having gravity section walls founded on rock. Let us further assume that navigation through this lock would continue from April until November each year, that each winter when navigation had stopped, the lock would be

pumped out, inspected, maintenance work would be done, and the lock would be rewatered the following April to be ready for resumption of traffic.

The first steps to be taken should be to develop quantitative data on the properties of concreting materials available within economic range. data on the performance of concrete made with these materials, data on the performance of concrete in similar service elsewhere, and data on the environmental effects that the concrete should withstand in service in the proposed system. The next phase of the study should be to develop concrete mixtures, to select construction practices, and to test concretes prepared according to these mixtures, using these practices to determine their relevant properties and to observe their behavior as they interact with the appropriate environmental influences in simulated service testing. Finally, specifications would be prepared and the system constructed.

The relatively unique feature of the environment that would need to be given greatest attention in this case is the evaluation of the effect upon the concrete of its exposure to the air from November to April each winter following the water soaking it received from April to November each year. When our studies at the exposure station near Eastport were begun, there was no combination of materials, mixture proportions, and construction practices that we knew how to specify that would produce concrete that could be used to make test specimens that could be placed thereon in November with any assurance that by April they would be other than in a state of complete disintegration. Soon we found that concretes made with some cements lasted longer than those made with others; concretes made with some aggregates lasted longer than those made with others; concretes made

to some mixture proportions lasted longer than others, and so on; however, the major finding was that any concrete could be given the greatest improvement in frost resistance if it were mixed with a foaming agent that caused air voids to be disseminated through the binder so that the spacing of the bubbles was not greater than 0.008 in.

Thus, as we would select specifications requirements for the concrete to be used in this system, we would prepare requirements for the aggregate to limit the selection to materials having properties similar to those that gave better service in actual use in the region and in the simulated service tests; we would impose similar requirements on the cements; we would require mixture proportions to be used that had done likewise, and we would require the incorporation of an air-entraining admixture shown to have the property of providing the desired level of entrained air in the paste.

Doing all these things will greatly improve the probability that the system will provide satisfactory performance. However, recent work has revealed that this would, in this case, not necessarily be sufficient, because concrete is a material that, when incorporated into the system of which it is to be a part, is a fluid mixture which only develops its significant properties over time after placement, and the rate at which these develop is itself a function of the interaction of the properties of the concrete and those of the environment. All the specimens that have been put on the test rack near Eastport were fabricated and cured elsewhere, in a different environment, and installed there in a relatively mature condition. After installation, no one of them has ever been exposed to temperatures below freezing for more than about six hours, since there

are two tide cycles per day. The hypothetical lock is to be constructed in this environment, and the concrete is to be exposed to the winter air all winter. The significance of these factors becomes apparent only after some fundamental considerations.

The increase in volume undergone by water during its change of state from liquid to solid is about 9 percent. Water will not undergo this change at its normal freezing point if it is either under other than normal pressure, contains dissolved salts, or is present in pores of sufficiently small size. It is thus not possible to freeze all the water in any concrete, no matter how low the temperature may fall, and conversely, the lower the temperature--and the longer the ambient temperature remains at a given low level--the more of the water in a given concrete will freeze. Data now are available showing that at our exposure station near Eastport the ambient temperatures that are encountered and the duration of exposure of the concrete to them are such that substantially none of the water in any concrete that is much more than one foot from the surface of the concrete ever freezes. Similar data suggest that a very large specimen in the same environment, exposed at a location above high tide, might during a typical winter experience temperatures below 28 F to depths of as much as 6 ft below the surface.

Concrete is a permeable material. If a pore in concrete is more than 91% filled with water and the temperature of that water falls below its freezing point, part of the water will freeze and undergo an increase in volume. The remaining unfrozen water will be placed under hydrostatic pressure and will tend to move through the permeable pore space to regions of lower pressure or into other pores. If the thermal gradient, the cooling, rate, the rate of frost penetration are low; the permeability high; the

duration of exposure to freezing temperatures short, the concrete may experience no adverse effects, even if a substantial portion of its pores that are of a size large enough to contain freezable water are more than 91 percent filled, since the excess may be able to escape to other regions.

Another factor that influences the response of critically saturated concrete to freezing is the strength of the solid material. This influence is difficult to evaluate separately from other variables, since the processes by which concrete increases in strength are processes which concomitantly reduce the quantity of freezable water, reduce the fractional volume of pore space of sizes capable of containing freezable water, and reduce permeability. Thus, when it is observed that concrete becomes more frost resistant with increasing maturity, and increasing strength, it is difficult to assess the degree to which the increased frost resistance results from increased tensile strength of the material making up the walls of the pores that are critically saturated, from the decrease in fractional volume of such pores, or from the decrease in saturation. It has been shown, for example, that in the absence of an external source of water entering the concrete, a concrete should have the water content of its originally water-filled spaces reduced below critical saturation and thus become frost resistant upon achieving the degree of maturity indicated by the development of an unconfined compressive strength of 500 psi. Other studies have shown that, where there is an external source of water--and perhaps other complicating environmental effects--as at the surface of a pavement to which deicing chemicals are applied, otherwise good, properly air-entrained concrete will only achieve frost resistance when it has matured to the extent indicated by having achieved and unconfined compressive strength of 4500 psi.

To return to the hypothetical lock at Calais, Maine, it is the indication of very recent studies that concrete subjected during a period of seven or eight months to a hydrostatic head of about 50 ft and thereafter exposed for four or five months to severe winter air temperatures needs to have matured to the compressive strength level of about 4000 psi if it is to be frost resistant, even if all other appropriate precautions are taken in the selection of materials, mixture proportions, and construction practices, including the provision in the binder of a satisfactory air-void system. In the absence of data such as those just mentioned, it is unlikely that specifications for a system in which structural loadings do not require strengths above, say, 2000 psi would insure the use of concrete mixtures that develop 4000-psi compressive strength prior to freezing of the concrete in the soaked condition.

Before leaving the discussion of interactions ~~topic~~, I would like to point out that the sort of approach suggested in this discussion is being taken not only by workers concerned with the performance of concrete as a material but also by some of those concerned with the behavior of structural elements composed of concrete. Recently I received for review the final report of an extensive research project concerned with the time-dependent volume change of concrete due to sustained load. The report begins with the statement: "Concrete possesses many behavioral properties which are, as yet, not thoroughly understood or even completely defined. When used as a structural material, the problems associated with this lack of understanding have, to date, been solved by empirical methods.... The phenomenon of creep--time dependent volume change due to load--remains

as a classic example.... Extensive tests aimed at studying the time-dependent deformation of loaded and unloaded concrete have continued since the first decade of this century....numerous hypotheses have been presented which attempt to explain creep...If one were to list all the parameters affecting creep of concrete, one needs list all the items associated with the manufacture and utilization of this material.... In addition to the obvious interrelated effects of different mixture proportions, constituent materials, curing conditions, and stress conditions, are factors such as moisture exchange and variation, temperature change and variation, specimen size and shape, and admixtures. When one considers the complexity of concrete and its time-dependent structural and chemical non-homogeneity, the conclusion that any change in its composition or its environment will, as a consequence, affect its volume stability is inescapable. The parameters which are significant, though inseparable in actuality, will be dealt with under eleven general categories."

Further along in the report we find the conclusion that the primary influence of aggregate is in its restraining effect on the potential volume instability of the products of hydration of the cement. Variations in aggregate particle size and grading permit use of leaner mixtures. Different types of aggregate present varying degrees of restraint, which depend on their moduli of elasticity. The pore character of the aggregate indicates the amount of water than can be absorbed, the rate of absorption and drying.

After reviewing the effects of all 11 categories of parameters, the report states: "The ideal prediction method would be one which would include

all the possible variables...however this approach is not practical. Effects of variables such as mixing time and consolidation, for example, cannot be included, since the range of these factors is not known. Whether concrete may be considered an ideal composite hard material or an ideal composite soft material has been questioned. It has been shown that for concretes using normal weight aggregates the behavior is that of a composite soft material, that is, the compliances are added. The cement paste, on the other hand, can be considered a composite hard material."

Time-dependent volume change due to load is only one facet of concrete behavior and, indeed, often a minor facet. Our laboratory has conducted creep studies largely to provide a basis for more accurately estimating the stress in concrete structures from measurements of strain.

Unsolved Problems

In my introductory comment I proposed that the asking of the proper questions regarding the extension of knowledge of the consequences of the interaction of concrete properties with environmental conditions would delineate the unsolved problems in predicting the behavior of concrete. As is true of all aspects of the search for truth, the really difficult problem is asking the proper questions. Last year more than three billion tons of concrete were produced--one ton for every living human being. Concrete, being ancient and ubiquitous, is assumed to be understood when actually we still do not understand the mechanisms by which it gains its strength, and we still do not have adequate theories to predict deformation or failure. I believe we need to ask questions concurrently on a

variety of levels, and we need to encourage workers trained in a wide range of disciplines to approach these questions. We need to ask why the constituents of cements react with water, how their atomic structure and its defects, dislocations, and substituents influence the rate and consequences of those reactions. We need to ask how the products of these reactions acquire their cohesiveness, continuity, strength, volume stability, and chemical resistance and what modifies these properties in what directions and to what degrees. We need to ask questions about all the kinds of rocks and minerals in the earth's crust that turn up as concrete aggregate constituents--questions relevant to the contribution of the properties of these materials to the properties of concrete--questions relevant to the interaction of the properties of these materials when incorporated as inclusions in a cementitious matrix with the properties of the environment in which the concrete serves. To date most of these questions have been approached by pure trial studies. One takes the cement one has and the aggregates one has and makes concrete according to the recipe one has; all of which one may have gotten from his grandfather. If he is a researcher, he may weigh the ingredients with greater care, and he may pay more concern to the "cleanness" of the ingredients than if he is a constructor of sidewalks. But the researcher, if he elects--or is directed--to investigate the interaction of concrete with temperature, or with neutrons, or with paper mill waste, will normally make concrete test specimens, will expose these to the existing influences or simulations thereof in the laboratory, and report, in due course, that recipe "A" yielded the most commendable behavior and recipe "N" the least commendable. Seldom will he learn why.

I suggest, therefore, that the unsolved problems are unsolved because we do not yet know why concrete behaves as it does.

In conclusion, I wish to explain briefly why I did not discuss the utility and application of the specific techniques of testing that are in use in the study of concrete. We have a battery of such tests ranging from the simple to the highly sophisticated and from the well known to the very poorly understood. However, these are used to measure properties of concrete not to predict behavior. The most widely employed nondestructive procedure is looking at concrete with the human eye, a technique about the employement of which a large book could, and should, be written. The most widely employed group of procedures that are described as "nondestructive tests" are those that do not measure strength but are believed to measure something related to strength that may be used to estimate strength. These include a variety of techniques for determining one or another resonant frequency of vibration; for determining the velocity of propagation of one or another type of mechanical disturbance, most frequently a compressional wave; and for determining the rebound of a hammer or pendulum. To the extent that these provide a basis for calculating approximate values for such mechanical properties as Young's modulus, or shear modulus, or Poisson's ratio, or coefficient of restitution, they are useful; what is lacking is an appreciation of the relation of these properties to most kinds of behavior. Other nondestructive procedures include radiography and the use of electrical or magnetic fields to indicate the location of voids or inclusions such as reinforcing steel; the use of electrical resistance, electrical conductance, neutron attenuation, nuclear magnetic resonance, microwave attenuation or

change in wave form, or other techniques to measure moisture content; the use of gamma radiation to measure density; the use of a wide variety of embedded sensors to measure stress, strain, moisture content, temperature, pore-water pressure, internal relative humidity, and such properties. Perhaps this is what I should have described here today. However, I have chosen rather to discuss what we might one day do with these bits of information rather than how we today obtain them.